Gary Demos

My personal history in the early explorations of computer graphics

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G. Demos Los Angeles, CA, USA gdemos@earthlink.net Abstract Gary Demos discovered computer graphics while hearing a computer-generated film presentation at CalTech in 1970 by John Whitney Sr. Gary then began working under the direction of Ivan Sutherland in Utah to develop early computer graphics hardware and software. In 1974 Gary and John Whitney Jr. started the "Motion Picture Project" at Information International to produce computer generated simulated scenes for movies (Futureworld, Looker, and Tron) and commercials. These early computer-generated visuals were quite challenging given the level of software and hardware technology available in the 1970's. In 1981 Gary and John left Information International to form Digital Productions, where they produced effects for the movies Last Starfighter and "2010", which were both released in 1984. Digital Productions used the Cray XMP computer, together with the Digital Film Printer that they had developed at Information International. Following a hostile takeover by Omibus of Digital Productions in 1986, Whitney/Demos Productions was formed, using a Thinking Machine parallel computer. This paper describes the technical challenges and achievements of this early visual computing.

Keywords CGI \cdot Computer graphics \cdot Scene simulation \cdot Visual effects

John Whitney Sr. 1970–1971

When I was a college student in 1970 at CalTech, I was fascinated by computers, and the mathematics that they enabled. John Whitney Sr. as visiting teacher presented amazing 16 mm movies of dots and lines, moving in time with music, created by computer. I was particularly amazed by the rich colors and deep blacks that he created using Kodachrome movie film. His enthusiasm for experimental filmmaking with computers was contagious, and I began to explore the intricate visual patterns that could be created by computer.

CalTech provided me with an excellent undergraduate education in physics, mathematics, and electrical engineering. Although I did not finish my senior year, I particularly enjoyed a senior/graduate class entitled "Introduction to Fourier Optics", which gave me an general understanding of lasers, lenses, and electro-optical components. All of these basic technical foundations were utilized in my subsequent work.

It should be noted that computer science was not an accredited degree subject in 1971, for either undergraduates or graduate students. Computers were, at that time, considered a tool in support of other scientific disciplines, and not in-and-of-themselves a discipline.

Evans and Sutherland 1972–1974

As a consultant to an educational movie (by IBM) about computers, I became aware of the work of Ivan Suther-

land and Dave Evans (as professors), and of Ed Catmul, and Fred Parke (as graduate students) at the University of Utah. They were exploring "shaded surfaces with hidden surfaces removed" where the physics of light interacting with surfaces was being crudely modeled with a few hundred polygons. I was fascinated by the potential of this work, and I contacted Ivan Sutherland to see if he was interested in applying this computer technology to movie making. I found that he shared this same interest, and I joined him (as an apprentice) at the Evans and Sutherland Computer Graphics Company in 1973, and worked on several essential computer graphics technologies under his direction. These included a large two-pen data table for creating three-dimensional polygonal surface data, Ivan's own "hidden surface" algorithm, and the development of the first DRAM-based frame-buffer for color image display.

The University of Utah became our first customer for the frame-buffer system, which consisted of 32-boards, cost \$80000, providing only $512 \times 512 \times 8$ -bit display. However, some features of this system were forward looking, including hardware zoom and pan, color lookup tables before the DAC's, and multiple realtime digital video input and output ports.

Another fascinating aspect of this project was the development of a DEC PDP-11 DR11-B test interface for testing the Mostek 4kbit Drams, since the memory chip industry had not yet established its own testing procedures. Of the first eight chips delivered to us, we found that seven were bad. Of the next eight chips, three were bad. At that point we gave our testing software (all ones, all zeros, wandering ones and zeros, and random numbers) and the tester circuit to Mostek, after which all the chips we received were good.

I was quite surprised that there was a great deal of interest in "painting" into the frame buffer with the pen and tablet. I felt this was a trivial use of the expensive system, since all that was involved was a loop to put the current color in a memory location matching the position of the tablet pen. However, a great deal of excitement was created by this simple use of the frame buffer, since apparently the use of random-access in the frame buffer's memory was very new and interesting to everyone. There was also excitement about the ability to cycle and update the four color tables (now called lookup tables, or LUTs) driving the DACs (now integrated with LUTs as RAMDACs). Again, I felt this was a trivial use of the lookup tables (making pseudo-color animations), which I had considered the basis of color spaces for getting the most out of the limited 8-bit-per-pixel frame buffer memory. In the subsequent several years, however, Alvy Ray Smith developed and published more broadly useful mappings for the DAC lookup tables. After Ed Catmul and Alvy Ray Smith graduated from the University of Utah the went to the New York Institute of Technology where they ordered a 24-bit-per-pixel threewide version of our frame buffer, providing them with the first full-color-capable random-access frame-buffer system. This system became a central tool for their subsequent work.

Another interesting part of the frame buffer development was learning about RGB color reference CRT video monitors. We produced the video 0.4 "gamma" in analog using a diode ladder after the DAC. Further, we found



Fig. 1. Cube, cone, and sphere scene with color fringing, copyright 1978 Information International

Conrac monitors that used the original NTSC color phosphors, having a substantially better red and green color purity than the SMPTE-C phosphor colors that were becoming ubiquitous at that time. The quality difference between an RGB signal to the monitor vs. an NTSCcoded color signal (which was significantly degraded) also amazed me.

It should be noted that the University of Utah at this time was unique in having a computer graphics graduate degree program. Many of the graduate students went on to become key figures in the computer graphics industry. For example, Ed Catmul and Alvy Ray Smith founded Pixar (Ed is currently the president of Pixar). Ed showed the first "picture-texture" mapping technique, using the parametric values of bicubic patches to lookup pixels in the texture map. Also, Jim Clark founded Silicon Graphics, which for many years was the largest computer graphics workstation company. I was privileged enough to be invited by Dave Evans and Ivan Sutherland to attend portions of Ed Catmul's and Jim Clark's Ph.D. thesis presentations. There were many others of special note at the University of Utah, including Gary Watkins, Bui Tuong Phong, Fred Parke, Frank Crow, Martin Newall (the creator of the "teapot"), and Richard Riesenfeld. Hank Christiansen, as a visitng professor from BYI, used the Watkins algorithm together with his "color fringing" method to color the stresses in deforming objects. Hank also created deformation techniques for threedimensional polygonal objects using "displacement vectors".

In 1975, Jim Blinn also entered the Utah graduate program, and immediately began using the frame buffer in the manner that I had anticipated, as a tool for computer graphics algorithms.

Picture/Design Group 1974

In 1974, Ivan and I joined up with Glen Fleck and John Whitney Jr. to work on starting the "Picture/Design Group". Glen Fleck had been a designer with Charles and Ray Eames, very well-known educational film and exhibit designers. Our first project was a test for Carl Sagan's "Cosmos" project, which at that time was going to be a feature film at Wolper Productions. For this project, I immediately discovered that the random number libraries available on the DEC computers showed unnatural radial patterns when using more than a few thousand stars in galaxy simulations. I therefore developed my own random number generator from a combination of available algorithms, after studying the literature on the subject. No single algorithm was random and pattern-free with hundreds of thousands of stars. I found that combinations of algorithms, some multiplicative, some additive, as well as others that I developed, provided the best source of random numbers. I authored a paper to share with my colleagues on this work, although it was never published.

Another activity was the continued development of Ivan Sutherland's recursive hidden surface algorithm. I worked on the Rand Corporation's DEC PDP-11 computers in the very early morning hours each day. I discovered that recursive subdivision was very sensitive to precision problems, and I presented these problems to Ivan, which I felt were fundamental to this type of algorithm. Although we made many successful images using Ivan's recursive algorithm, I was of the opinion that the algorithm was not sufficiently stable to support moving image production. Through this work with Ivan, however, I gained substantial expertise in synthetic image rendering technology, and I developed an understanding of the subtleties of hidden surface algorithms.

In 1974, there was little infrastructure for "Venture Capital", and the Picture/Design group was not successful in finding a source of funding. Ivan went to Rand Corporation, and then later to CalTech as a professor.

Information International 1974 to 1981

John Whitney Jr. and I decided to continue our pursuit of the potential of computer simulated images. John had worked with Information International Inc. (also called "Triple-I") on the movie "WestWorld" in 1973 with author/director Michael Crichton. Information International was the world leader in digital film scanning and recording technology for microfilms, and they were very interested in moving toward color scanning, and recording, for still images, motion pictures, and color halftone printing.

Information International's board of directors included founder Ed Fredkin, a technology entrepreneur from MIT, president Al Fenaughty, and noted fathers of artificial intelligence Marvin Minsky from MIT and John McCarthy from Stanford (the inventor of the LISP computer language). After our presentation to the board, we were given approval to gradually build new computer graphics technology using their DEC PDP-10 and PDP-15 (in the III-15 version) computers.

FutureWorld

John Whitney Jr began marketing for us, and we soon found that Michael Crichton was planning a sequel to "WestWorld" called "FutureWorld" for summer release in 1976, to star Peter Fonda, Yul Brenner, and Blythe Danner.

I also discovered that there were some excellent computer engineers and mathematicians working at Information International, including Malcolm McMillan and Karol Brandt, who soon joined our "movie project". Other



Fig. 2. Cover of Computer Pictures magazine, August 1980, copyright 1980 Information International



Fig. 3. Peter Fonda's 4000-polygon head database from FutureWorld, copyright 1976 Information International

in-house computer experts (many from MIT) also pitched in to help us get started. Of particular note was Dan Cameron, a digital designer who had been a lead engineer for many of Information International's digital scanning and film recording systems. We also interviewed designers, and acquired Art Durinski who recently graduated from UCLA's design school.

For "FutureWorld" John Whitney Jr., Dan Cameron, and I worked out a three-camera photography system, using pin-registered Mitchell 35 mm cameras. We took simultaneous frames from 0 degrees, 45 degrees, and 90 degrees of Peter Fonda in both full-body and upper-torso, although we only used the head data from the upper torso. We made up Peter in all white, and we placed black fiduciary dots and crosses all over his face and body, to provide multi-camera registration points. Large 30" prints were made from the images. Mal McMillan wrote software that extended Ivan's two-pen idea to undo lens perspective and distortions, thus recreating the threedimensional form of Peter Fonda from multiple views. Mal and I also worked together to implement Ivan's idea of "skinning" to create polygons in ribbons as we filled the detailed surface. The final data for Peter's head was about 4000 polygons.

Meanwhile, I worked with Frank Crow to develop a scanline-based hidden surface and lighting renderer, starting with the work of Bouknight. The Bouknight algorithm had the advantage that it could support transparency, unlike the Watkins algorithm. I believed that scanline-based algorithms were needed, since I was designing the renderer for 2300 scanlines (3012 horizontally by 2300 vertically). Area-based algorithms, which were the other main line of research in rendering algorithms, increased computational time with the square of the number of scanlines (with the area of the image), whereas scanline algorithms were only a little slower than linear ones as a function of the number of scanlines. However, we added Phong-shaded specular hilights, which required area-based computations for the highlight regions. Further, when using transparency, the rendering time increased with the average depth complexity (the average number of layers visible in depth prior to the background or prior to, and including, an opaque surface). I felt that transparency was a required attribute of rendering realistic scenes. We used transparency for not only glass and windows, but for clouds, ground-fog, smoke, flames, and other essential simulation effects. I also insisted on the need for multi-thousand-line resolution. It was nearly a decade later before anyone's renderers, other than my own, were able to exceed one thousand lines for movie production. I was certainly proud that we produced nearly a minute of computer simulation for FutureWorld at 2300-line resolution in 1976.

In addition to the computer simulation, I also created a digital composite for the "Samurai warrior" scene. This scene used a locked-off shot of an empty decompression chamber combined with an action shot from the same camera location. The scene had three Samurai warriors materializing inside the chamber. Using the difference between the empty and actor scenes, I isolated the warriors for processing. It was necessary to use a garbage matte as well, in order to eliminate the shadows from the difference. I created an algorithm that sampled the warrior's pixels and created close-packed triangles the same color as the underlying pixel. The triangles began large and gradually decreased in size until they approached single-pixel resolution, completing the materialization. I believe this was the first digital composite used in a movie. I used 3012×2300 resolution for this scene.

Close Encounters test

In 1977, we worked with Vilmous Zigmond, Steven Spielberg, Julia Philips, Michael Philips, and Doug Trumble on tests for a scene in "Close Encounters of the Third Kind". We tested the concept of free camera movement scene tracking, wherein "witness points" at known locations were visible in the scene. Using 4" spherical light globes at known positions on the set, the camera was moved freely on a crane in tests for the scene where the space ships enter the arena. There was particular interest in the agile "cuboids", which were simulated white cubes that zipped around the people in the scene in free flight.

Mal McMillan developed an automated scan tracking system using the PFR, where the "center of gravity of the density" of the witness points was used to track their two-dimensional locations in the frame. Mal's tracking algorithm was relatively fast, needing only a few seconds per frame to track the points. From this data, Mal developed an inversion/relaxation algorithm, combined with data smoothing, to determine the location and orientation of the camera within the scene for every frame. This method was better than camera mount tracking, since the minute gate weave of the film could be tracked precisely using witness points.

Such systems are now also called "3D tracking" or "3D match move" systems. These systems allow very high precision tracking of three-dimensional scenes, so that computer generated images can be placed "into" the scene with perfect registration. It is a form of three-dimensional compositing.

We then simulated objects that would appear to be within the scene in a careful three-dimensional sense, with emphasis on the "cuboids". This was also the first time that I worked on glow, flare, and halation effects, in order to make the cuboids appear to glow and change colors in a fog-shrouded environment.

At this early time, we were not able to gain enough of the production team's confidence to get the contract for effects for the movie (which went to Doug Trumble using motion control and models). However, we gained significant confidence in our ability to place simulated objects within real scenes with a free-moving camera.

Short logo productions

After FutureWorld, we started exploring short severalsecond productions, given that several minutes per frame limited our production capacity. Television logo's seemed to be a good fit for our early capacity, with the plan to gradually work up to 30-second commercial production. Working with Frank Crow, we developed a mechanism for "co-planar polygons", which allowed surface normals to follow tiny edge contours. This allowed fine object edges to kick off highlights, greatly helping to create a realistic object appearance. Many real object edges are naturally rimmed with highlights.

We also felt it was beneficial to build an "affect-effect" simulator to create halation, star filter, and glow effects from bright highlights on the simulated objects. I wrote a program in the film recorder that drew hundreds of thousands of tiny faint vectors away from every bright pixel, using my pattern-free random numbers to control the direction and brightness of each vector line (computer generated lines were called "vectors" at that time). This method faithfully simulated the camera and lens optical effects generated by bright highlights when photographic real scenes.

At the 1977 Siggraph in SanJose, I brought a 35 mm projector to the filmshow audience of a hundred people. I believe that this was the first time that many people had seen photorealism and high resolution in computer simulations. I also believe that the audience was surprised by the glow and halation star effects being simulated on the highlights of simulated objects. Many attendees said that this was an "aha" for them, showing that simulated moving objects could appear completely real.

About this time, I began working with Jim Blinn, who was finishing his Ph.D. at the University of Utah. Jim developed a scanline-based bicubic-patch algorithm, which had computational performance that scaled linearly with vertical resolution, except when area-oriented processing was applied. However, our use of texture mapping, bump mapping, and reflection mapping in conjunction with the bicubic patches nearly always yielded area-scaling performance. This high computational requirement limited our use of bicubic patches to short sequences when using bicubic patches, and our normal processing used the much more computationally-efficient polygon rendering.

We created about 100,000 lines of code for the renderer, which was a mixture of Fortran and assembler code. We called this renderer "Tranew", meaning new transparency algorithm. The resulting algorithm was efficient at 2300 scanlines, and provided two key lights, ambient light, backlight, transparency, bicubic patch support, texture mapping (as initially demonstrated by Ed Catmul), and bump texture (from Jim Blinn) using a height field to perturb surface normals. We also added reflection mapping, using the surface normals to lookup reflection images in an environment map. Our own Mal McMillan developed mathematical tools for creating spherical and cylindrical reflection environments from photographs, and from multi-image computer renderings.

One notable project at this time were the "Pyramid Films" logo, with a transparent pyramid refracting a rainbow from sunrise on the ocean. Mal developed a "trochoidal" bump map, which we animated to create the



Fig. 4. I.I.I. museum, copyright 1979 Information International

moving waves. Another notable project was the KCET productions (PBS in Los Angeles) logo, with a postcard opening up into a night time flyover of Hollywood. The entire night street scene was compressed into the flat card, and expanded as the card flipped up to the camera, so that the camera could fly into the city.

Our computer systems

By today's computer standards, our computational equipment was extremely crude. The system software was functional but provided only basic support. However, we worked hard to make the best of our computers, which were considered powerful at the time. We used the PDP-10 computer, which occupied most of a room. We later were able to use a prototype computer known as the "Super Foonly F1" developed in conjunction with recent Stanford graduates Phil Petit, Dave Poole, and Jack Holloway. This ambitious computer had 5000 ECL chips, and used twenty 100-Amp 5V switching power supplies. Unfortunately, the Foonly was only marginally reliable, and would fail about once a day. Because of this, we needed to watch it around the clock in order to ensure that the processing needs were met for our various production projects.

At that time, a megabyte of memory was the size of a refrigerator, and a 40Gbyte disk was the size of a washing machine. One way that we were able to achieve acceptable performance was the use of memory-to-memory transfers between computers, known as DMA (direct memory access). We also built a variety of custom digital systems, using fast (but small) 4kbit SRAM memories and specialized ALU (arithmetic logic unit) and dedicated multiplier chips. The computer industry was very confused about the proper size of digital computing "words", and we had a hodgepodge of 8-bit, 9-bit, 16-bit, 18-bit, 32-bit, and 36-bit computers. This benefited us to some degree, since 9-bit, 18-bit, and 36-bit precision provided better computational precision for computer pixel computations. In practice we were completely intermixed between power-of-two and multiple-of-9-bit word and byte sizes. I attempted to use very little floating point, since it was quite slow at that time. I wrote numerous assembly code routines supporting accelerated 9-bit, 18-bit, 36-bit, and even 72-bit computations. I found that we needed 72-bit integer precision (as opposed to 36-bit integer) for depth computations, in order to provide for accurate intersections between nearly planar objects in large panoramic environments. The shadow algorithm that Frank Crow developed for me depended upon accurate shadow umbra plane intersection with objects when creating the shadow boundaries.

The digital film printer

Beginning with the FutureWorld project, we used the I.I.I. programmable film reader, or PFR, as a base system, to which we added color film scanning and recording capabilities. We adapted available lenses and color filters for the scanner and recorder cameras. The PFR used a 5" diameter cathode ray tube (CRT).

Using this system, we performed a mock digital film printer test, where we scanned images shot by LucasFilm Industrial Light and Magic (ILM), and performed a simple reproduction. Richard Edlund, then at ILM, supervised our test. We discovered that we lost substantial resolution and tonal detail in performing this copy. However, we believed that we knew how to improve upon the mock printer to create a digital film printer (the DFP) that would perform well as a digital replacement for optical film printers.

At about this time, we added Mark Grossman and Tom McMahon to join Karol Brandt in our hardware team, and we added Bill Dungan, Craig Reynolds, and Larry Malone to our software team.

The DFP design used a 7" diameter CRT, with a 1 mil spot, allowing us to achieve about 5000 pixel resolution. The spot itself was shaped somewhere between a Gaussian and a cylindrical shape (uniform spot), which made it optimal for recording and scanning resolution. Another key design element was an entirely new optical system, designed with Pacific Optical. In order to capture the scanned light behind the film gate, the light needed to be collimated to be nearly parallel, or telecentric going through the film plane. The collimated light was split into red, green, and blue with red/cyan and blue/green dichroic filters, with trimmer filters at each photomultiplier. A unique feature of the DFP was a set of fibre-optic light pipes surrounding the lens that were gathered to a fourth photomultiplier, which then provided an independent look at the CRT spot. This effectively gave a measurement of the light coming from the CRT for each pixel spot. Using this reference path measurement, the ratio of the light leaving the CRT to the light gathered by each photomultiplier, then yielded a direct measurement of the density at each pixel on the film. This color density measurement was processed using analog logarithmic amplifiers, subtracting the reference path, and then analog-to-digital (AtoD) converted using an 11-bit AtoD.

The color negative film, which was ubiquitous at the time, was the newly introduced EK5247 from Kodak. This

film was quite grainy by today's standards, but was relatively stable, allowing reasonably precise system calibration. In order to provide the most image area for the extra generation required when scanning, we used a VistaVision Acme-style Richardson movement. This movement pulled 4-perforations on the film, so norm 4-perf 35 mm as well as 8-perf VistaVision could be used for both scanning and recording. It was typical to scan VistaVision, and record 4perf. A custom camera housing was developed for us by Doug Fries, supporting the large optical path behind the film gate for the scanning dichroic filters, condensing optics, and photomultipliers.

The PFR used a programmable raster that we reproduced for the DFP, allowing scans to rotate, keystone, and resize. In this way, the optical resizing portion of scanning was handled directly in the scan. Further, anamorphic scanning was directly applied when needed. For recording, the raster was usually applied in a relative uniform manner (usually square pixels), with the pixel samples being computed with the anamorphic squeeze taken into account. Thus, there was no need for anamorphic optics, and we were thus able to handle widescreen movies directly, including mixing flat VistaVision elements with anamorphic computer simulated images to create an anamorphic 35 mm widescreen result.

For film recording, a 12-bit to 12-bit hardware lookup table provided a known transformation to yield specific densities on print, and corresponding specific densities on a mid-light calibrated print. In this way, the mapping of light, as computed by the renderer, as well as density from the scanner, could be processed to yield deterministic calibrated results. The blending of texture maps from the scanner, in density units, and pixels from the rendering algorithm, in light proportions, became a key system requirement. The use of film density units was not sufficient.

The speed performance of the DFP was 600 ms per pixel for scanning, and 200 ms per pixel for each color (red, green, and blue) for recording, although two or three passes over the red was usually required. For our 3012×2304 resolution, a scan only took four seconds, and a frame recording only required about eight seconds. This was substantially faster than we could process the data in our large general-purpose mainframe computers. Some of the optical mechanical units, or OMUs, were capable of both scanning and recording, with a change of camera head. The recorder head used a color filter wheel between the CRT and the film, whereas the scanner had the color splitting and sensing system behind the film plane.

We therefore built the "DFP pipeline" consisting of 3-D cross-color lookup tables and interpolators for each of the three scanners, a 3-D cross-color table for colordifference matte compositing (such as blue-screen), and a general purpose computational unit for general processing. The general purpose unit, using microcode,



Fig. 5. Cover of Computer magazine, November 1978 (note recursive texture mapping), copyright 1978 Information International

could emulate the PDP-10 instruction set that we used in the Foonly computer. The DFP pipeline also contained a new 1000-line frame buffer with an Ikegami color CRT monitor. All of the pipeline, including the frame buffer, was built using the Intel 4kx1 SRAM, which was small but fast. We built a memory board having 72 such chips, and used the board at many places throughout the pipeline.

Although we began the development of the DFP in 1978, it several years to complete all of the portions of the system. Some portions, such as the frame buffer, became operational in 1979. The film scanners and recorders became operational in 1981, being delayed primarily due to long development times on the optical portions of the system.

Further explorations at I.I.I.

One area that we thought would have substantial potential was three-dimensional character animation. Mal McMillan wrote realtime animation algorithms, and an interpreted language for controlling them based upon "Castle". I wrote math macros such as "slow in" and "slow out" for the otherwise assembler-only III-15 18bit-word minicomputers. Mal developed 3-space path spline-based techniques for expressing and controlling motion during animation. Using these tools, Mal created a butterfly animation and a worm animation that played realtime on the graphics screen. The realism of the animation movement gave us confidence that we could begin to explore three-dimensional character animation.

Another area of emphasis at this time was increasing memory and computational efficiency so that we could create high scene complexity. In 1978, we did a test for LucasFilm of the Star War's "X-Wing" ship. Art Durinski encoded a 15000 polygon wing on our two-cursor data table. Using symmetry with four instances of the wing and one fuselage, a 75000 polygon X-Wing fighter was created. Mal developed 3-D motion algorithms for creating a "peal off" of the X-Wing fighters, combined with a sweeping three-dimensional camera move. The resulting motion, when rendered, created a dramatic space scene. For motion, we created lower detail versions of the X-Wing for long shots, and used the higher detail version for medium and close shots. We showed these results to LucasFilm in the summer of 1978. In the summer of 1979, we were given permission to publicly show the X-Wing, and it became the cover of the August 1979 "Computer" magazine, concurrent with Siggraph in Chicago. This image,



Fig. 6. Database built from actress Susan Dey for the "Cindy" head model for the movie Looker. Art Durinski and Larry Malone are drawing polygonal reference lines on Susan Dey. Copyright 1980 Information International

combined with early spacecraft motion tests, created substantial interest that year in the potential of high scene complexity, high resolution, and photorealistic lighting.

The X-Wing needed to have a dirty "used future" look consistent with the Star Wars movies. For this, we applied a "color-per-vertex" technique using dirty brown tones combined with normal smooth shading (and coplanar polygons for edges). We called this database of dirt the "dirtabase". At about this time, John Whitney Jr. coined the term "Digital Scene Simulation" to describe our rendered synthetic image process.

Because I.I.I. was working on color halftone recording onto full-paper-size film, I wrote a conversion and filtering program to create the halftone dots directly from the raster. The natural raster size for the Computer magazine cover at $8^{"} \times 10^{"}$ was 4500×5600 creating a 133-line screen for Y, C, M, and K at 30 degree angles. Using the "chromalin" color halftone printing preview systems, we made numerous experimental color separation tests until we were satisfied that we could create direct halftones of any of our color images. As it turned out, we never needed this capability again, since our use of $4 \times 5^{"}$ Ektachrome and negative film at 6144×4096 resolution was preferred in future publications as the color image master.

In 1979, we proposed simulated space ships for the movie "Meteor". However, at that time, the producers thought of computer-generated images as being line im-



Fig. 7. I.I.I. Juggler "Adam Powers" with Ken Rosenthal in motion-capture suit, and vector version, copyright 1980 Information International

ages. We therefore produced 3-D line images representing monitor footage for Meteor. However, it was clear to us that photoreal space-ship simulation would be possible in the near future.

I worked on 3-D stereoscopic tests in 1980 with Murray Lerner, which in 1982 became dual-70 mm Magic Journeys for the Kodak Pavilion for the opening of Disney's Epcot theme-park in Florida. Eight minutes of stereoscopic computer graphics were produced as optical elements for that show (which utilized extensive 65 mm opticals). We found, through testing, that 3-D stereoscopic production benefited from the inherently infinite depth of field of computer simulation. We also found that care was needed in the choice of colors and the treatment of objects near the edges of the frame. By experiment, we were able to produce amazing three-dimensional stereoscopic simulated scenes.

Looker

In 1980, Michael Crichton wrote the script for the movie Looker, based upon John Whitney Jr's conviction that photo-real simulated people would be practical in the next ten to twenty years. The movie Looker was about using simulated actors in commercials. Six minutes of effects were produced, including three-dimensional construction of actress Susan Dey's head and body. We also



Fig. 8. Coke cans (note lettering detail on top of can, as well as reflections), copyright 1985 Digital Productions

created line-based and text-based scenes matched with the shaded images, using "hold takes" where a reference mark 100-frames prior to the first frame allowed a single negative to be run through multiple cameras. This created first-generation images with a composite of multiple image sources. We also produced the anamorphic widescreen "Looker hypnotizing gun effect".

The face and body simulation used a four-mirror setup, which allowed a single front movie camera to see from above, from the left, and from the right. This allowed a single frame to provide all of the views necessary to create a three-dimensional body and face surface, using Mal McMillan's updated perspective and distortion removal software. We used the same white makeup and fiduciary marks, as well as drawing lines for polygonal boundaries directly onto the face and body.

The juggler

Having this multi-mirror setup allowed us to take moving images of Ken Rosenthal juggling and doing a back flip. Using the data from these multi-views in each 35 mm film frame of motion, Mal McMillan was able to create a datasmoothing and 3-D reconstruction system providing one of the earliest examples of 3-D simulated performance animation.

We named the juggler Adam Powers and gave him a tuxedo and top hat for his juggling magician's performance.

Considering the future

John Whitney Jr. began commenting in magazine interviews that he believed that the degree of photorealism in both appearance and motion was becoming a matter of creative choice, and not of technical limitation. John talked about recreating performances of famous actors from the past. I speculated that long and medium shot photorealism for actors, animals, and alien creatures were becoming practical. I also speculated that crowds of such simulated characters of creatures would become an important cinematic tool. John talked with Michael Crichton about how interesting and effective it might be to simulate dinosaurs in a movie. We were able to see much of the potential of the computer simulation medium at this time.

Tron

Beginning in 1979, John Whitney Jr. began working with Steven Lisberger and Bill Kroyer on story development and scene planning for "Tron".

Because of the Juggler, Disney could see that 3-D simulation was becoming viable as a new medium in and of itself.

Craig Reynolds, who I hired as a recent graudate from MIT's architecture/machine group, created the LISP-

based technology he called ASAS, the actor/scriptor animation system. Craig used ASAS to create a broadlycapable front end to control the Tranew renderer. All of the scenes produced by I.I.I. for Tron used ASAS.

The producers of Tron decided to spread the work between multiple facilities. The other facilities included Digital Effects (the "bit"), Abel (line-drawing opening), and Magi (light cycles). III scenes were the major final sections of the movie including the MCP (master control program) face, solar sailor on the sea of simulation.

The DFP film recorder was used to make VistaVision elements for the 65 mm film.

John Whitney Jr. and I left I.I.I. in the Spring of 1981, while Tron was just starting production.

Tron was released summer 1982.

Digital Productions 1981–1986

At the time we began at I.I.I. there was little awareness of the potential of computer simulated images. However, by 1981, we had demonstrated enough of the potential that we found some industry investment interest in the potential. A graphics company of the time named Ramtec, which made frame buffers, invested in John Whitney Jr. and myself to allow us to form Digital Productions.

The Cray computer

I decided to use the Cray computer for rendering. The Cray used 64-bit floating point exclusively, had 16Mbytes main memory, and 64 Mbytes IO subsystem memory (two 35 mm frames, one still frame). As before, the disks were like washing machines (12 of them at 600 Mbytes each, for 7 Gbytes total). The Cray's special performance came from 64-long "vectors", of 64-bits each, organized to efficiently pipeline computations. Contrary to the common wisdom of the time, which said that three-dimension and three-color computations were not suited to vector processing, I found that vectors could be used to gain optimal Cray performance on computer simulated rendering.

Since I was in a hurry to write our renderer and demonstrate some basic capability, we started with Hank Christiansen's "Movie.BYU" Watkins algorithm. We were quickly making images on our Ramtek frame buffers. Just as quickly, my team replaced the heart of the Watkins algorithm with a Bouknight-style algorithm to support transparency, and we added highlights and shadows. We knew that Frank Crow's umbra-based shadows were computationally expensive with high scene complexity, so we began working with low-detail shadow objects, that fit precisely into high detail space ships.

Our initial emphasis was on high scene complexity and computational efficiency, since we were preparing for large scale simulated special effects production.



Fig. 9. Gloomy Castle Room using "dark lamps" to simulate radiosity effects, copyright 1985 Digital Productions

Larry Yaeger, Craig Upson, Fred Bradford, Jim Hardy, Steve Williams, Larry Luther, Ron Moskowski, Mitch Wade, David Ruhoff, Andy Davidson, MaryAnn Morris, and Emily Nagel formed our initial software development team. We soon added Beth Leitner, Kevin Rafferty, Jack Green, Kathy Prestera, Michael Kory, and others to our "encoding" team, and Jim Rygiel, Brad Degraf, and others to our "technical director" team. We used the Evans and Sutherland PS300 line-drawing perspective displays and large dual-cursor Talos tables for encoding, and the IMI graphics perspective display system for building motion.

Last Starfighter

We began working with Miguel Tejada-Flores and Ron Cobb on production planning for a script by Jonathan Betuel called "The Last Starfighter". At this time, video games were becoming popular. The Starfighter script featured video games as a path to recruit pilots for real starships. Given that we were just starting Digital Productions, we felt that the initial delivery of crude video game graphics would naturally evolve into the complex photoreal spaceship scenes. Working with Gary Adelson and Eddie Denault as producers, and Nick Castle as director, we began production on 250 scenes and 22 minutes of full-screen special effects.

We created complex objects, such as the 250,000 polygon "Gunstar" ship, 50,000 polygons for the "deck fighters", and 150,000 polygons for the "mother ship".

We chose 2560×2048 resolution, since the Ramtek frame buffers were 1280×1024 (one quarter the area). Our computations on the Cray produced simulated pixels with 64-bit floating-point accuracy. We truncated and fixed them to 12-bits (for each of R, G, and B) for film recording (and for scanning), and dithered the values to 8-bits (per color component) for display.

In late 1982, after the completion of Tron and Magic Journeys at III, we were able to acquire the DFP OMU's for our film recording and scanning. Jim Rapley and Larry Sinclair joined us from I.I.I., and they worked with David Ruhoff and Bob Allison to build an interface between the Cray high-speed channel (100 Mbytes/second) and the OMU interface. Phil Chen became our expert on ensuring that the DFP and the film Lab (MGM) remained in perfect daily calibration. Mal McMillan joined our software team and Art Durinski joined the encoding team. (At the same time, Larry Malone, Tom McMahon, and Craig Reynolds went from I.I.I. to form the Symbolics graphics division, further refining the LISP-based approach to computer scene simulation.)

Ron Cobb quickly learned the art of creating threedimensional objects in the computer, developing intricate space ship designs for the movie. Ron Cobb was also fascinated by the motion choreography potential of the realtime line-preview in the IMI displays. Ron Cobb worked closely with the software and technical directing team of Brad Degraf, Larry Luther, and Ron Moskowski.

The Last Starfighter was released in the summer of 1984. This was only two years after the release of Tron, yet represented a large step forward in scene complexity and detail.

The renderer

With Larry Yaeger and myself leading the team, we built a high efficiency renderer having one million lines of code, about 1/4 of which was the Cray assembler. We used "overlays" in the linker to allow us to switch between various modules within the limited memory. The Cray XMP had two processors sharing 16 Mbytes of memory, so we needed to keep the renderer below 8 Mbytes to be able to fit two into memory simultaneously. Our overlays included the fluid-dynamics particle system, the compositor, the fractal renderer, and the main full-featured renderer. Walter Gish wrote the fractal renderer overlay that we used for moonscapes and planetscapes in Starfighter, together with the compositor and the main renderer for the ships in the foreground.

The main full-featured renderer was capable of rendering entire complex scenes during a single scan down the image raster. The compositor, however, allowed layered computing to optimize rendering time using multiple rendering layers, composited together. We stored a transparency channel with each layer for front-to-back compositing, but we preferred back-to-front compositing, to avoid needing to store the transparency channel. However, the main all-in-one renderer supported transparency texture maps in addition to picture texture, bump texture, and reflection maps. The transparency texture allowed us to perform composites directly in the renderer, without using the compositing overlay. For example, the explosions in the Last Starfighter were all texture pictures with transparency maps that defined the opacity/transparency of each explosion. We often had dozens of explosions during the battle scenes between the Gunstar ship and the deck fighters. Compositing required clear definition of depth precedence, whereas the use of transparency texture and picture texture in a scene automatically processed the depth of each explosion with respect to other ships and explosions.

For reflection maps, we favored the use of the cube (six faces), so that we could render six 90-degree width and height views from a given location, and then use the resulting six images as a reflection environment from that location.

Unlike previous texture mapping, which required bicubic patches or quadric surfaces, I devised a simple method of creating and interpolating parametric (u, v) values to allow texture mapping over arbitrary topology polygonal objects. This required much less computation than bi-cubic patches, and allowed our renderer to perform picture and transparency texture very efficiently.

I added numerous light sources to the renderer with programmable falloff to simulate point sources, line sources, and area sources. Further, we could place multiple lights within the scene with specific angular radiation patterns. Combined with shadows, these simulated lights allowed us to create rich scenes.

In addition to normal light with color, rolloff function, and angle, we also built specialized unreal lamps called "dark lamps". These would pull light out of a scene, rather than adding light to it. This was useful for augmenting the automatic shadow and lighting algorithms, in order to remove light from areas. Instead of luminance and luminosity, we referred to these dark lights as having "gloominance" and "gloominosity".

2010

Upon the completion of Last Starfighter we were contracted to create the Jupiter planet scenes for 2010 (the sequel to 2001) for director Peter Hyams. 2010 was another 70 mm production, and we worked with Richard Edlund, who had left ILM to form Boss Films. Richard provided us with a 65 mm camera, which we outfitted on the DFP recorder OMU. The optics and filters for VistaVision and 4-perf were optimized for fast recording. However, the 65 mm off-the-shelf El-Nikor lens and color filters lost several stops, requiring about two minutes per frame instead of about ten seconds.

The key to the creation of the swirling clouds of Jupiter was the creation of a Navier-Stokes fluid dynamics particle system by Larry Yaeger and Craig Upson. A flow field was encoded using wind directions taken from Voyager spacecraft images of Jupiter from JPL. Ron Gless made a painting with much higher detail and color fidelity using the JPL images as a guide. We scanned a three-wide-vertical-panel image of the Jupiter "snake-skin" painting, which we scanned as three frames in VistaVision on the DFP. Using a frame-blending overlap, we created a single snakeskin at $6 \text{ k} \times 2.5 \text{ k}$ resolution to be wrapped as a cylinder onto the Jupiter sphere. Using the fluid-flow-particle overlay, the texture image would be "advected between" each frame by interpolating the force field vectors and applying the resulting force to five

million colored particles. The particles were then filled into a pixel raster to create a texture map for the next frame.

Since Jupiter was a polygonal object, the dent and collapse was handled by normal displacement vectors applied to the vertices. Since the texture was mapped onto the polygons, the flowing fluid deformed with the sphere. We produced about five minutes of "digital Jupiter" scenes in 65 mm for 2010.

2010 was released in December 1984, making it the second major motion picture effects project that we finished in 1984.

John Whitney Jr. and I were recognized by the Academy of Motion Picture Arts and Sciences in March of 1985 with a scientific and engineering award for the "photo-realistic simulation of motion picture photography by means of computer generated images, 1984".

Commercials and logos

Our next emphasis was on the production of commercials and logos in order to keep our substantial staff and computing capacity busy. We produced logos for major companies, such as the AT&T sphere, which ran for fifteen years on network television. The AT&T Logo was produced working with designer Saul Bass.

We also produced high-budget commercials for the Pontiac Fiero, the Chevy Astro-Van and Mercedez Benz, all featuring photo-realistic cars. The Astro-Van scene not only used simulated vans, but we also photographed people leaving a real van, and scanned the frames in VistaVision on the DFP for creating composites.

For STP oil treatment, we produced a visual simulation of a transparent working car engine, including a camera fly through of the oil path within the engine.

Character animation

Working with Mal, and following on Mal's pioneering 3-D animation work, Larry Luther, Ron Moskowski, Allan Peach, Brad Degraf, Lynn Benner, MaryAnn Morris, Stephan Fangmaier, Mike Ullner, Yun Chen Sung, Shelly Lake, Bill Kroyer, and Chris Baily developed new 3-D animation tools, and helped to further improve the renderer. We began to see expressive character animation, which we used in tests and commercials. I was my belief at the time that 2-D animation would eventually be replaced by 3-D character animation.

One of our projects was to connect the IMI to a "Waldo" hand-operated sensor provided by Jim Henson. Brad Degraf and Larry Luther tested the idea of directly controlling the 3-D line-drawn character in the computer by use of two such hand-operated Waldo controls. This was quite facile, and we decided that we could develop an effective 3-D animation system based solely upon such controls. Mary Ann Morris and Lynn Benner also developed a phonetically-drive lip-position system for driving dialog from syllables. Their system used a multi-displacementvector capability that I built into the renderer, which allowed blend proportions of any number of end positions, or of displacement vectors (or both). We called this "multi-level interpolation". We felt that we were very close to a facile system for controlling speech, as well as for controlling other facial features such as smiling, eye expressions, eyebrow expressions, etc.

John Whitney Jr. was particularly interested in this character animation development, and he convinced Mick Jagger to create a music video using simulated characters for his song "Hard Woman". Within the lower budget per frame of music video, John, Bill Kroyer, and Chris Baily were able to create expressive animated tube figures in a simulated day-of-the-dead festive world. The primary input was film that we shot of a person performing moves for the animated characters. The person, as usual, was covered with fiduciary witness marks. The frames of film were projected onto the 2-cursor data table, and were projected directly onto the line-drawing animation screen.

Even with these sources of animation motion, much of the production used direct animation control from the dial boxes and parameters that could be selected for smooth motion to the desired postures.

Compositing with the DFP

Of additional interest was the use of green-screen compositing using the DFP. I suggested that we use green instead of blue, since the blue record of film is very noisy. I worked with Michelle Feraud to create a clean matting algorithm for partially-covered pixels, which we used to put moving images of Mick into the simulated scenes of the video. Michael Whitney supervised the green-screen photography of Mick Jagger. Bill Villarreal also began making hardware improvements to the OMUs to support this work.

We did a test with Peter Anderson and Peter Ellenshaw of Disney of our digital blue-screen compositing for the elephant movie "Baby". They provided very helpful advice on how to improve our composites. As we refined the compositing algorithms, we began to gradually include the use of blue-screen and green-screen composites in our productions.

We also recreated Mal's witness point tracking using in-frame-buffer-memory tracking, instead of tracking in the scanner. Mal's new version of the smoothing and relaxation/inversion algorithms performed flawlessly. We also began to gradually include witness-point tracking "match-moves" in our productions, to excellent effect.

For still frames, in addition to 4×5 and 8×10 Ektrachrome and negative, we began using 35 mm 8-perf Kodachrome 25 at 5120×3072 resolution. Kodachrome 25 has a wide color gamut and a deep black, although the

inter-layer interactions are large. Using our 3-D crosscolor lookup table, we were able to invert the inter-layer interactions so that we could use Kodachrome like any other color film, creating calibrated matches to our motion picture film negative.

Of particular interest was our discovery that 11-bits are needed for wide-range image media such as Kodachrome. Since our pixels were inherently noise-free using the Cray 64-bit floating point, we could truncate accurately to 9, 10, 11, and 12-bits. We found that contour bands, showing both steps and hue changes, were visible below 11 bits on smooth surfaces of objects such as the Gunstar ship. The contour bands were barely visible at 11-bits, and became invisible at 12-bits.

A decade later, I received the Motion Picture Academy "Scientific and Engineering Award" recognition in 1995 along with Dan Cameron for digital scanning technology, shared with David DiFrancesco and Gary Starkweather of Lucasfilm/Pixar, and with Scott Squires of ILM.

I also received the 1996 Motion Picture Academy Technical Achievement Award recognition for "digital compositing systems" along with David Ruhoff, Michelle Feraud, and Dan Cameron.

Whitney/Demos Productions 1986–1988

After Digital Productions was taken over by Omnibus in a hostile takeover in 1986, John Whitney Jr. and I formed Whitney/Demos Productions. I chose a Thinking Machine CM-2 with 16,384 processors in a SIMD (single instruction, multiple data) configuration. Having had success with the 64-long vector registers of the Cray XMP, I felt that the massively-parallel architecture would be effective.

We found that some operations, such as the sorts required for hidden surface and transparency computations were only moderately efficient. However, lighting computations, and other mathematically-intensive computations for every pixel were extremely efficient.

We also teamed up with Symbolics, to utilize software and hardware developed by our former team members from I.I.I. I very much enjoyed programming the Symbolics and Thinking Machine computers in LISP. In the years since them, I have often reflected on the crude nature of the "C" and "C++" languages in comparison to the rich LISP environment that I had available with the Symbolics.

As a pilot showcase project, Craig Reynolds of Symbolics and Philippe Bergeron, MaryAnn Morris and others in our group worked together to create the animated short "Stanley and Stella". Craig showcased his latest ASAS-like automated characters in the birds in this short, which he called "boids", which was short for "bird-oids".

Our technical team also consisted of Karl Sims, Karol Brandt, Larry Sinclair, Michael Whitney, MaryAnn Morris, Mitch Wade, Jim Hardy, Craig Burkhardt, Mal McMillan, Peter Walford, Yun Chen Sung, and David Ruhoff.

We did election graphics in 1988 for CBS, using the new D1 digital video tape systems from Sony, and disk arrays from Abekas. Although component digital video was a significant improvement over previous NTSC ana-



Fig. 10. Gary Demos with his $1280 \times 720/72$ fps camera on the cover of Television Broadcast magazine, January 2000

log systems, I still found it difficult to work at the very reduced resolution of standard video.

John Whitney Jr. worked with Michael Bedard to develop tests for three-dimensional animation of his "Sitting Ducks", although we were not able to get this production launched at the time (but we came close to launching a television series with CBS).

In 1988, John Whitney Jr redirected and reorganized the company to become US Animation, and I left to form DemoGraFX.

PDI and Pixar

Although I had nothing to do with Pixar or Pacific Data Images (PDI), both companies persevered through the following years until computing power became sufficient for their digital animation requirements. PDI became Dreamworks animation. Both companies followed the model that I felt was going to be successful, which was the production of movies in their entirety (not just effects sequences for movies). I also felt that 3-D animation had substantial potential as a new story telling medium, and I believe that this is now broadly recognized. Disney, Rhythm and Hues, Sony Pictures ImageWorks, and others have also produced epic works in 3-D character animated movies.

High-definition and compression

In DemoGraFX, I took much of what I learned in high resolution imaging, and the weaknesses that I found in



I apologize to those who worked with me on these various early computer image simulation efforts, who I forgot to mention here. I worked with so many talented people over this time span that I probably forgot to mention a few key names. However, everyone who contributed to these efforts has my gratitude, for helping to create an exciting time where everything was new, and every week we saw something that was being done for the first time. It is not possible to have more than one era of first times for computer simulated images. I was very privileged to be able to help create, and to experience together with others who also created along side me, many new things, which revealed to all of us a wondrous potential for a truly new medium. The computer became, in that era, a tool for creativity, instead of a being exclusively a tool for engineering and mathematics.



GARY DEMOS was fascinated by the hardware and software challenges of computer graphics, beginning in the 1970's. Gary pursued this interest through Information International (1974-1981), Digital Productions (1981-1986), and Whitney/Demos Productions (1986-1988). In 1988 Gary formed DemoGraFX, which became involved in technology research for advanced television systems and digital cinema, as well as consulting and contracting for computer companies and visual effects companies Gary began to specialize in research relative to high performance cameras and digital compression based upon the discrete cosine transform. In 2003 DemoGraFX was sold to Dolby Labs. Gary is presently working solo in the development of new wavelet-based and optimal-filter-based moving image compression technology for high bit-depth and high dynamic range.